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A Tribute to Simon, and Some -Too Late- Questions, by a Cognitive Ergonomist

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Abstract: Herbert Simon's proposal of a "science of design" is fundamental to the many researchers in cognitive psychology and ergonomics. This is due to Simon having applied the information processing paradigm to design problem solving and having elaborated various characteristics of design that are essential in the cognitive design problem solving processes. Empirical studies on design have also led, however, to results that lead to nuance Simon's approach. We first expose the elements proposed by Simon underlying our viewpoint on design. Then we present some reservations with respect to Simon's approach, especially concerning his tendency to underestimate in design (i) the specificity of ill defined problem solving, (ii) the importance of problem representation building, (iii) the role of "nondeterministic" "leaps", and (iv) the obstacles met by the problem decomposition method. We also briefly present another paradigm, i.e. "situated cognition", adopted by design researchers in reaction to Simon's rational problem solving. Even if it makes up for some of Simon's limitations (among those cited above, especially for the role of constructing problem representations), we don't advocate this alternative approach above Simon's. We will propose an interpretation of the differences between the two, claiming that they are not contradictory, but complementary, because they focus on different aspects of design. We will conclude by some —too late— questions to Simon.

[1] This text corresponds to a communication delivered at the International Conference In Honour of Herbert Simon "The Sciences of Design. The Scientific Challenge for the 21st Century", Lyon, INSA, 15-16 March 2002.
A revised version of this text is being elaborated. All remarks and suggestions are welcome.

Un hommage à Simon et quelques questions tardives par une chercheuse en ergonomie cognitive

Résumé : La proposition faite par Herbert Simon d'une "science de la conception" est fondamentale pour un grand nombre de chercheurs en psychologie et ergonomie cognitives. Nous lui devons en effet l'application du paradigme du traitement de l'information à la résolution de problèmes de conception et l'identification de caractéristiques essentielles de cette activité cognitive. Cependant, des études empiriques sur la conception ont conduit également à des résultats qui nous conduisent à nuancer l'approche de Simon. Nous présentons d'abord les éléments proposés par Simon qui sous-tendent notre approche de la conception. Nos réserves par rapport à l'approche de Simon concernent notamment sa tendance à minimiser certains aspects de la conception, liés à (i) la spécificité de la résolution de problèmes mal définis, (ii) l'importance de la construction de représentations de problèmes, (iii) le rôle de sauts "non déterministes", et (iv) les obstacles que rencontre la méthode de décomposition de problèmes. Nous présentons brièvement une autre approche, la "cognition située", qui répond à certaines insuffisances de l'approche de Simon. Nous proposons toutefois que les deux approches ne sont pas contradictoires, mais complémentaires, parce qu'elles se focalisent sur des aspects différents de la conception. Nous conclurons par quelques questions —trop tardives— à Simon.

Mots-clés : Conception, Psychologie cognitive, Ergonomie cognitive, Etudes empiriques, Résolution de problèmes mal définis, Représentation de problèmes, Cognition située.

Table of contents

Only human pride argues that the apparent intricacies of our path stem from a quite different source than the intricacy of the ant's path. (Simon, 1999, p. 82)

The present conference in honor of Herbert Simon and his proposal of a "science of design" brings together researchers from many disciplines. Herbert Simon's ideas on design are indeed so broad that many fields of science (both "natural" and "artificial") are concerned. They have, for example, been fundamental to the viewpoint on design held by many researchers in cognitive psychology and ergonomics. This is due to Simon having applied the information processing paradigm to design and having identified and elaborated various characteristics of design that are essential in the cognitive processes involved in design problem solving. The present paper will try to explore the nature of this legacy. Trying to exploit the corresponding basis provided by Simon, we have met difficulties, however, in the interpretation of results obtained in empirical studies on design problem solving. The reservations and questions provoked by these apparent limits in Simon's approach will constitute the object of the second part of this paper. Researchers focusing on "situated cognition" have also reacted upon Simon's "rational problem solving" paradigm. We will briefly present Donald Schön's view representing this alternative position in the domain of design studies. An interpretation of the differences between the two approaches will be proposed, claiming that they are not contradictory, but complementary, because they focus on different aspects of design.

1. The basis provided by Simon for design research in cognitive psychology and ergonomics

This section presents the main elements proposed by Simon (and colleagues, especially Newell[2], cf. Newell & Simon, 1972), that are fundamental to the viewpoint on design held by many researchers in cognitive psychology and ergonomics. Together with Newell, Simon indeed elaborated the information processing paradigm, which afterwards was applied to design problem solving. Subsequently, in his analysis of design, Simon identified various essential characteristics that form the basis of the approach taken toward this activity by many, if not most, researchers in cognitive psychology and ergonomics.

1.1. Simon's proposal for a "science of design"

"Sciences of the artificial" is the qualification that Simon proposes in 1969[3] for the "sciences (or science) of design". In the French translation by Le Moigne (Simon, 1974), "sciences of the artificial" has become

[2] *Sciences of the artificial* is being dedicated actually "to Allen Newell in memory of a friendship".

[3] The quotations (and thus the pagenumbers) in this text come from (Simon, 1999), which is the third printing of the third edition of the book. This third edition, from 1996, is a revised version of Simon (1981) (it also introduced a new chapter on complexity,

the subtitle (and in the singular, "Science de l'artificiel"), the main title having become "Science of systems" ("La science des systèmes").

In his book which bears this title and which is central to the present conference, Simon considers these sciences of design as sciences in their own right, as distinct from the natural sciences that are traditionally considered as "Science"—even if in 1987, he proposes to "compromise" on the perhaps less "pretentious" qualification of "the art and science of design" (Simon, 1995, p. 245)[4]. As he writes in the chapter entitled "The science of design: creating the artificial" (in which engineering design is the reference), "Historically and traditionally, it has been the task of the science disciplines to teach about natural things: how they are and how they work. It has been the task of engineering schools to teach about artificial things: how to make artifacts that have desired properties and how to design." (Simon, 1999, p. 111) Indeed, if the natural sciences are concerned with the necessary, with how things are, design is concerned with the contingent, with how things *might* be (Simon, 1999, p. xii). The italics in the previous sentence are ours, for design indeed consists in specifying: I do not consider implementing the resulting specifications to be a design activity (see our definition of design in the section "Characteristics of design problems").

So, designers are "concerned with how things *ought* to be ... in order to *attain goals* and to *function*." (Simon, 1999, pp. 4-5) Simon's thesis (see Note 3) is indeed that "certain phenomena are 'artificial' in a very specific sense: they are as they are only because of a system's being molded, by goals or purposes, to the environment in which it lives" (Simon, 1999, p. xi). That is why symbol systems (or "information processing systems") are "almost the quintessential artifacts [:] adaptivity to an environment is their whole *raison d'être*" (Simon, 1999, p. 22).

Many elements of this proposal which are central to our analysis of design have been detailed in Simon's seminal book and in a series of papers that are concerned with design in a more (Simon, 1971; Simon, 1973; Simon, 1995; Simon, 1999) or less direct manner (Kaplan & Simon, 1990; Kulkarni & Simon, 1988; Langley, Simon, Bradshaw, & Zytkow, 1987; Okada & Simon, 1997; Qin & Simon, 1990). The main aspects of these elements will be discussed below.

"Alternative views of complexity"). The 1981 edition already constituted a revised edition of the original text dating from 1969. The concluding section of the present paper will discuss the nature of the various revisons. The first, 1969, edition collected the three Compton lectures that Simon gave in 1968 (plus a 1962 paper on "The architecture of complexity: hierarchic systems"). The 1981 edition alternated revised versions of these three chapters with the three Gaither lectures delivered by Simon in 1980. In the Compton lectures, Simon developed his thesis of the contingency of artificial phenomena that had been central to much of his research, at first in organization theory, next in economics and management science, and later in psychology. In 1981, he amended this thesis and expanded it to several additional fields, especially (engineering) design and architecture. The 1969 edition already contained the chapter "The science of design: creating the artificial"; the 1981 version added to this a chapter on "Social planning: designing the evolving artifact".

[4]The Simon (1995) paper is the text of a lecture delivered in 1987 at the *First International Congress on Planning and Design Theory*. In this text, Simon presents an approach to design that is much closer to ours than is the one presented in *Sciences of the artificial*. We will come back to this 1987 lecture later on in our text. One of our —too late—questions to Simon concerns our surprise that this position, which had already been adopted in 1987, was not reflected in his 1996 version of the "The science of design" chapter.

1.2. Simon's analysis of design as a type of cognitive activity rather than a professional status

The "intellectual activity that produces material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state" (Simon, 1999, p. 111). Engineering, medicine, business, education, law, architecture, and painting are "all centrally concerned with the process of design" (ibid.). Simon indeed defends the approach that "design" is not restricted to engineers: "Engineers are not the only professional designers. Everyone designs who devises courses of action aimed at changing existing situations into preferred ones." (ibid.) This view that design is a type of cognitive activity, not a professional status restricted to "designers", is nowadays adopted by many, if not most, researchers in cognitive psychology and cognitive ergonomics of design —even if most do not adopt as large a circumscription of activities "centrally concerned with the process of design" as Simon does. We will come back to this point below in the section "Other characteristics of design problems".

1.3. Simon's analysis of design problem solving as an information processing activity

Simon's analysis of problem solving as an information processing activity and of design as problem solving, and thus of design as an information processing activity, refers to two important theoretical positions:

- Analyzing the human cognitive activity of problem solving as a goal-seeking information processing activity, an approach elaborated by Simon together with Newell (see Newell & Simon, 1972), and
- Applying this approach to design problems.

The application of the goal-seeking information processing model to design was not made right from the start (i.e. in 1972), but this was not due to any theoretical reasons. Newell and Simon (1972) note that their study is concerned with tasks that are short (half-hour), with moderately difficult problems of a symbolic nature resolved by "intelligent adults" working individually[5]. The elaboration, over a period of some 15 to 20 years, of their 1972 information processing model was based on algebra-like puzzles (cryptarithmetic), chess, and symbolic logic problems. Newell and Simon (1972) note that the thinking involved in, e.g., "designing a house, discovering a new scientific law, ... creating new music ... are largely beyond the current state of the art", i.e. as it was in 1972. However, "they are in fact part of the same story [the authors] wish to tell" (p. 7). In later years, together with colleagues and Ph.D. students, Simon began tackling such problems. Research conducted, e.g., on insight problems such as the "classic mutilated checkerboard problem" (Kaplan & Simon, 1990), represented, according to the authors, "a major extension of the standard information processing theory of problem solving" (p. 376). In the same vein, the processes involved in scientific discovery have been investigated in various settings (Kulkarni & Simon, 1988; Langley et al., 1987; Okada & Simon, 1997; Qin & Simon, 1990).

The information processing analysis of problem solving in terms of problem states (initial, intermediary and goal states) linked by transitions implemented by operators, as proposed in Newell & Simon (1972), provides the fundamental schema for the investigation of different types of problems by many authors in

[5] The present text is restricted to individual design.

the early years of cognitive psychology. Already very early, Reitman (1964), e.g., very judiciously adopted this approach for problem solving. Reitman indeed distinguishes different types of problems in terms of the three-component vector {A, B, ->} in which A stands for the initial, B for the terminal state or object, and -> for "a process, program, or sequence of operations". In his paper, Reitman presents examples of six different types, which, even if they "do not span the domain ... do illustrate the range of activities to which the framework may be applied" (p. 284). The problems analyzed are all in the domain of problems involving the "transformation or creation of states, objects or collections of objects". Reitman proposes that types of problems differ according to A, B and -> being specified more or less. Generally, in design problems, the component that is specified explicitly, even if poorly, is B. B indeed is usually specified at an abstract level, by way of its function and of some constraints. A and -> are nearly always underspecified, but correspond —implicitly— to the state of the art in the domain (the knowledge that exists, with respect both to domain objects and methods). Reitman (1964) applied his analysis to a particular design problem, i.e. composition of a fugue.

1.4. Simon's analysis of design as "satisficing"

Simon qualifies design as a "satisficing" activity, that is, designers are looking for good, acceptable, satisfactory solutions rather than for the one and only best, optimal solution from all the possible ones (Simon, 1995, p. 246; Simon, 1999, p. 119).

Simon's "satisficing" concerns, however, rather evaluation than generation activities in design; it is used in a critical, rather than a generative sense. Simon considers that designers are concerned with "finding alternatives" (Simon, 1999, p. 121). However, "seldom will the goals and constraints be satisfied by only a single, unique design", that is alternative (Simon, 1995, p. 246). "Once we have found a candidate we can ask: 'Does the alternative satisfy all the design criteria?'" (Simon, 1999, p. 121) However, "seldom will it be feasible to examine all possible designs to decide which one is, in some sense, optimal." (Simon, 1995, p. 246) So, designs are evaluated by comparing them in terms of "better" and "worse". Simon coins the term "satisficing" to describe the decision procedures used with this aim.

2. 2. Some nuances with respect to Simon's position

After the previous section, which introduced the elements proposed by Simon that are fundamental to our view on design, the present section discusses some points on which I want to propose some nuances with respect to Simon's approach. These proposals are based on the analysis of data collected in empirical studies on design activities, conducted mainly in professional work settings, but also in experimental conditions (Cross, Christiaans, & Dorst, 1996; Pahl, Badke-Schaub, & Frankenberger, 1999).

The discussion begins through a characterization of design problems from the viewpoint of cognitive psychology and ergonomics, which opens this section. Indeed, some differences with respect to Simon's position already appear here (see also Goel and Pirolli 1992, who adopt Simon's approach).

2.1. Other characteristics of design problems

After the presentation of my definition of design activities, several characteristics of design problems will be presented that Simon did not been propose, or that he considered differently.

2.1.1. My definition of design activities

Various definitions and characterizations of design have been proposed. The element that I consider to be essential is that design is a specification activity. Design consists in specifying an artifact, given one or more objectives to be satisfied by that artifact. This design specification activity proceeds by elaborating such a precise and detailed representation of the artifact that its implementation is completely defined. Implementing the resulting specifications, however, is not considered to be a design activity.

N.B. There is a misunderstanding —not in Simon's mind of course— surrounding the term "artifact" as object of design. In the context of design, this term, rather than pertaining only to material objects (buildings or machine-tools), refers to all objects that intelligent entities (human or artificial) may create, that is, material or immaterial (music, software or other procedures). The antonym of "artifact" is "natural" (object) —it is not "immaterial" (object).

Simon proposes a somewhat larger definition of design when he writes that "everyone designs who devises courses of action aimed at changing existing situations into preferred ones" (Simon, 1999, p. 111). We concurred above with his idea that design is a type of cognitive activity, not a professional status. However, we do not consider that, e.g., physicians prescribing remedies for their patients, are designers —their main cognitive activity will rather be analyzed as one of diagnosis (that is, a kind of structure induction problem solving, see below). However, their medical colleagues devising a new therapeutic protocol, e.g. for treating cancer, may be considered to be involved in a design process. In the same way, someone who is applying laws will not be considered a "designer", but the legal specialists drawing up new laws will.

2.1.2. Design problems in contrast to transformation and structure induction problems

Cognitive psychology classically distinguishes three types of problems, i.e. transformation problems, structure-induction problems (e.g. diagnosis) and arrangement problems (Greeno & Simon, 1998). More recently, design problems have often been presented as constituting the third category, but without authors making explicit the difference between design and arrangement problems, should one exist. Greeno and Simon (1998) analyze design problems as mixed, combining characteristics of induction and arrangement problems. In cognitive psychology, transformation problems are the types of problems that have by far been receiving the most attention, also by Simon and colleagues, particularly in the form of play problems (such as the Tower of Hanoi), rather than problems to be solved in professional settings.

Even if this problem classification is the reference in cognitive psychology, it does not tell us much about the specificity of design. In terms of the information processing framework proposed by Newell and Simon (1972), "design problems can be understood as problems of search in a space that contains many possible arrangements of the problem materials, only one or a few of which satisfy the problem criterion."

(Greeno & Simon, 1998)[6] A metaphor used to characterize solution processes adopted in order to solve "classical" problems is "searching through the set of possibilities". The corresponding metaphor for design problems proposed by Greeno and Simon (1998) is "narrowing down the set of possibilities". Constraints are used to guide this reducing. According to Greeno and Simon, design problems impose constraints mainly on the goal state, which is, nevertheless, specified in terms of general criteria, rather than as definite states or procedures. This makes them differ from transformation problems which mainly constrain the operators that can be used in achieving the goal state (initial and goal state are given in these problems). This characterization of design problems in terms of their goal state is "informative" in that it restrains the repertoire of problem solving methods that may be appropriate to solve these problems. The main problem solving method proposed and developed in (Newell & Simon, 1972), which is means-end analysis, would probably not be very useful in design. Indeed, this method presupposes that the current state of the problem (an intermediary problem-solution state) can be compared with a goal state in order to discover one or more differences between them (if so, it uses operators associated with each difference that may be capable of eliminating such a difference). It would indeed be difficult to establish the differences between two states specified at different levels, the current state of the problem being at a "concrete" level, its goal state generally being, at best, at an abstract level.

Simon (1999), however, asserts that no new and hitherto unknown concepts or techniques are needed to handle design problems[7]: "no qualitatively new components" need to be introduced in the classic general problem solving mechanisms (Simon, 1973, p. 197), no "special logic" is necessary (Simon, 1999, p. 115) —even if he "admits" that standard logic is to be adapted to the search for alternatives (Simon, 1999, p. 124).

We will come back to these points in the section on "Simon's tendency to minimize certain aspects of design".

2.1.3. Ill defined (vs. well defined)

The first point on which I would place a different emphasis than Simon concerns the analysis of design problems as being ill defined. Simon calls them "ill structured", whereas "ill defined" and "well defined" are the terms used by Minsky (1961)[8] and Reitman (1964). We adopt the "ill defined" - "well defined" couple, because we judge this characteristic as not only being a question of problem structure. As noticed by Reitman (1964), the continuum ranging from well defined formal problems to such ill defined empirical problems as composing a fugue is closely related to what the author calls "ambiguity". For ill defined problems, this ambiguity translates the scarcity or even absence of agreement over a specified community of problem-solvers regarding referents of problem attributes, permissible operations, and their consequences. This means that solutions to ill-defined problems are more or less accepted (in a specified community). The source and locus of this ambiguity, inter-individual variability, and problem ill-

[6]In his conclusion of the chapter on "The psychology of thinking" (which dates from 1969), Simon states that "the theory of design *is* that general theory of search" "through large combinatorial spaces on the outer side [of the human brain, that is] the side of the task environment" (Simon, 1999, p. 83).

[7]Exactly as he declared on the subject of ill-defined problems (Simon, 1973).

[8]Minsky (1961) does not speak of "ill defined" problems. He defines "well defined" problems: when we call a problem "well defined", "we mean that with each problem we are given some systematic way to decide when a proposed solution is acceptable" (p. 9).

definedness, are the "open constraints". These are according to Reitman (1964, p. 292) surely the most important in characterizing ill defined problems. An "open constraint" is a constraint "whose definition includes one or more parameters the values of which are left unspecified as the problem is given to the problem-solving system from outside or transmitted within the system over time." (pp. 292-293) In Reitman's approach to problem solving, a problem's constraints are the attributes defining its components. In this section, the focus will be on presenting my approach to design problems as ill defined; in a later one, Simon's position will be discussed.

Some authors consider design problems to be "ill defined" because they admit several solutions, others because there are open constraints in the problem specification. I consider a problem to be ill defined with respect to the nature of all three problem solving components, i.e. the initial specifications, the operators that may be applied to solve it, and the goal state —even if this goal state will generally be relatively more specified than the other two components (Reitman, 1964, see also above).

In a paper on "human nonadversary problem solving", Mayer (1989) presents a series of arguments that call into question four implicit premises of the information processing model (Mayer, 1989, pp. 54-55). These premises concern what Mayer (1989) calls "atomization", "componentialization", "mechanization", and "concretization". His remarks concerning "atomization" are particularly relevant here (the other ones will be referred to later on in the paper).

"Atomization" refers to a problem's atoms (i.e. states and operators) being clearly delimited, i.e. specified. This does indeed hold for well defined problems (even if Simon, in his 1973 paper, nuances the definitional status of this characteristic, see below). However, for ill defined problems, "determining the atoms ... is often the crucial part of problem solving rather than the starting point. Further ... the atoms may change as they are combined during the problem solving process." (p. 54)

With respect to attaining its goal state, a design problem being ill defined means that it admits several, more or less "satisfactory" solutions. It does not possess the first characteristic of the list that Simon (1973) established for well defined problems, that is, "a definite criterion for testing any proposed solution, and a mechanizable process for applying the criterion" (p. 183) do not exist for ill defined problems.

Related to this ill defined —and non atomic— character of design problems is that design problem solving cannot be analyzed as a linear two-stage process going from "the" problem specifications to "the" solution: problems do not pre-existing to solutions, both are built up simultaneously. Mayer (1989) presents this two stage "componential" character of problem solving as another premise of the information processing model being denied by the reality of ill defined problems.

Concerning the operators, the ill defined character of design problem solving has, at least, two sides. At a "local" level, even if designers have many pre-existing design methods available, this repertoire is not necessarily sufficient. Designers often have to "import" procedures from other domains, both technical and general, "common-sense" knowledge (Visser, 1995). Even if designers locally use pre-existing strategies, at the organizational level of the design activity, the articulation of strategies will not be pre-established (e.g. proceeding top-down and breadth-first). Design activity is organized opportunistically (Bisseret, Figeac-Letang, & Falzon, 1988; Hayes-Roth & Hayes-Roth, 1979; Visser, 1994).

2.1.4. *Other characteristics*

- Design problems are generally large and complex. Their composition also is often complex, each component having numerous relations with other ones. The number and character of these interrelations makes it hard to decompose a design problem into independent subproblems. (We will come back to decomposition as a problem-simplification method.)
- Solving a design problem involves handling representations from different domains (especially, design methods, the application domain, various technical and non technical domains).
- A design problem's complexity combined with the need for different domains of knowledge leads to design projects often requiring the collaboration of specialists from various professional domains.
- Generic knowledge is used of course in design problem solving. However, the reuse of specific knowledge, i.e. knowledge linked to particular design projects, plays a role that is more important than has traditionally been assumed —and thus examined— in approaches to problem solving.

2.2. Simon's tendency to minimize certain aspects of design

Many positions Simon adopts may apply to rather "simple", well defined problems, but they are unrealistic when dealing with the typical ill defined problems (professional) designers generally meet. This opinion will be further defended through four points.

2.2.1. *Underestimating the specificity of ill defined problem solving*

Simon's analysis of the ill defined character of design problems is, as noted, the first point where I put a different accent than Simon.

In his famous paper on "the structure of ill structured problems", Simon (1973) adopts the position that "there is no real boundary" between well structured problems (WSPs) and ill structured problems (ISPs) (Simon, 1973, p. 182). "There may be nothing other than the size of the knowledge base to distinguish ISPs from WSPs .... General problem solving mechanisms that have shown themselves to be efficacious for handling large, albeit *apparently* well structured domains should be extendable to ill structured domains without any need for introducing qualitatively new components." (Simon, 1973, p. 197) "In fact", Simon argues, "many kinds of problems often treated as well structured are better regarded as ill structured" (p. 182). "Definiteness of problem structure is largely an illusion that arises when we systematically confound the idealized problem that is presented to an idealized (and unlimitedly powerful) problem solver with the actual problem that is to be attacked by a problem solver with limited (even if large) computational capacities." (p. 186) The examples he presents are two types of problems analyzed in (Newell & Simon, 1972), i.e. chess playing and theorem proving.

"Typically" "ill structured" problems, such as (creative) design problems, may also, at first analysis, indeed be considered ill structured, judges Simon. However, reasoning on the example of designing a house, he argues that even a "typically" "ill structured" problem rapidly acquires structure, due to a designer applying strategies, such as decomposition (see below, section 3.2.4). "During any given short period of time, the architect will find himself working on a problem which, perhaps beginning in an ill structured state, soon converts itself through evocation from memory into a well structured problem." (Simon, 1973, p. 190) So, both chess playing and architectural design problems, even if they are ill structured "in the large", are well structured "in the small" (Simon, 1973, p. 191). "In the small" refers to the subproblems to be solved (in chess, playing one single move; in architect, e.g., designing a heating system or another component of a house to be designed), "in the large" to the global problem (in chess, an entire game; in architecture, the entire project).

Thus, for Simon, an ill structured global problem is rather smoothly amenable to a set of well structured subproblems. Designers start design problem solving by structuring their ill structured global problem, and then solve the resulting well structured problem and/or subproblems. "Nevertheless, there is merit to the claim that much problem solving effort is directed at structuring problems, and only a fraction of it at solving problems once they are structured." (p. 187)

Empirical observations on professional designers show that

- of course, such well defined subproblems exist, but they exist next to many other ill defined subproblems, and,
- even more importantly, there are not two separable phases in design —and most other types of "real"— problem solving, first structuring a problem, and afterwards solving it (cf. the non linear character of the design process referred to above). Of course, designers analyze problems, they decompose them, they interpret and reinterpret them, making them thus more manageable, easier to solve. However, such activities occur in an interspersed manner, and all through the design process, until late in the project. Many examples of this can be found in empirical studies on strategical aspects of design, especially studies detailing its opportunistic character (Visser, 1994).

With respect to ill defined subproblems remaining, even after careful analysis and decomposition, we may present the example of the way in which a mechanical engineer[9] handled the functional requirements. These were mainly the client's requirements but, in a first, global analysis, mechanical design colleagues had analyzed them and already listed specifically (in the "Tool Plates" specifications document) the operations that they judged necessary for the required functions. Nevertheless, these Tool Plates were not only consulted, but also completed, and even modified by the mechanical engineer (Visser, 1990).

The idea of designers proceeding in two main consecutive stages is the prevailing view in Simon's 1973 paper. Nevertheless, he occasionally is less "extreme" and seems to consider most problem solving as switching between ill defined-problem solving (which nevertheless consists in structuring the IPS into a WPS) and well defined problem solving (p. 193). "Each small phase of the activity appears to be quite well structured, but the overall process meets none of the criteria we set down for WPSs." (Simon, 1973, p. 194) Problem solvers —designers— can be considered to be "faced at each moment with a well structured problem, but one that changes from moment to moment" (Simon, 1973, p. 195).

If we agree with Simon that "there is no real boundary" between well defined and ill defined problems, we think that it has, at least, a clearly heuristic function to distinguish "typically" ill defined problems from "typically" well defined problems. Confronted with design problems, such a distinction makes it possible to anticipate, e.g., the particular characteristics presented above.

[9]This mechnical engineer was observed throughout his task of defining the functional specifications for the computerized control part of an automated machine tool installation.

2.2.2. *Underestimating the role of problem representation building*

Newell and Simon's information processing theory does not deal with changes in problem representation, as the authors mention explicitly (Newell & Simon, 1972, pp. 90-91). Problem solving is search *in* a problem space defined by the problem specifications. Among the subjects they observed, only one paid specific attention to choosing a problem space, i.e. a problem representation. Newell and Simon's focus is on the way in which, given a particular problem representation, a subject tries to solve that problem.

Greeno and Simon (1998) proposed that design consists in "narrowing down the set of possibilities" defined by a problem space. Simon (1999) seems to adopt this approach to design. At the beginning of the "Science of design" chapter, he asserts that design requires making a rational choice among a set of given, "fixed alternatives", "computing the optimum" (Simon, 1999, pp.114-119).

However, in a subsequent section, he observes that this position is not realistic: "in the real world", "design alternatives are not "given", "not given in any constructive sense", not "even in the quixotic sense" of "given" as the result of using a "computationally infeasible" algorithm. So designers, rather than starting with a set of given alternatives amongst which they have to choose, are concerned by "finding alternatives", by synthesizing alternatives. "Once we have found a candidate we can ask: 'Does the alternative satisfy all the design criteria?'" (Simon, 1999, pp. 119-121)

"But how about the process of *searching* for candidates?" Simon proposes means-ends analysis, i.e. the general strategy proposed in Newell and Simon's 1972 information processing theory, that is, identified in studies on cryptarithmetic, chess and theorem proving. This strategy requires that the designer is "able to represent differences between the *desired* and the present". GPS, the computer problem solving program designed to "model some of the main features of human problem solving" uses therefore a "*table of connections*, which associates with each kind of detectable difference those actions that are relevant to reducing the difference". "GPS then is a system that searches selectively through a (possibly large) environment in order to discover and assemble sequences of actions that will lead from a given situation to a desired situation." (Simon, 1999, pp.121-123) Complications arise, however, with as complex a problem as design often turns out to be. The integration of their sequences of actions or other solution-components into one global solution comes up against their non-additivity, their non-independence, and their interaction.

Then, finally, near the end of his chapter, in a subsection entitled "Problem solving as change in representation", Simon writes that "a deeper understanding of how representations are created and how they contribute to the solution of problems will become an essential component in the future theory of design." "Alternative representations for design problems" then becomes the final subject in Simon's program on the theory of design (Simon, 1999, pp. 132-134).

Elements for this "future" theory of design in which an important role is attributed to representations, their creation and modification, can already be found in research conducted by Simon and colleagues referred to above on insight problems and scientific discovery. The good news this research brings is that "the same processes that are ordinarily used to search *within* problem space can be used to search *for* a problem space (problem representation)." (Kaplan & Simon, 1990, p. 376)

Hence, studies such as (Kaplan & Simon, 1990) show the important role of representation in problem solving. They maintain implicitly, however, the idea that "the" representation is built at the beginning of the problem solving process, once and for all.

2.2.3. *Underestimating the role of "nondeterministic" "leaps"*

Simon does not deny that processes such as intuition may play a role in expert activities. "Intuition is a genuine enough phenomenon which can be explained rather simply: most intuitive leaps are acts of recognition." (Simon, 1999, p. 89). So, rather than on search, they are based on recognition, in chess, often pattern-recognition. In his section on intuition, indeed, Simon (1999) is concerned with chess grandmasters, whose "intuitive leaps" occur between the coding of physical chessboard position features and the memory representations of these positions as familiar configurations —that is, between elements already associated. Furthermore, these intuitive leaps occur within a domain whose number of components is limited (even if large).

"Interesting" design ideas often depend on "leaps" between domains —which immediately increases not only the number of possibly relevant candidates, but also the chance of links already existing. The "intuition" underlying leaps between, e.g., the problem of designing "unfurling principles" for future antennas, and (mental representations) of "umbrella" and other "folding" objects, such as "folding photo screen," "folding butterfly net," and "folding sun hat" cannot rely on pre-existing associations. This is neither the case for leaps between the problem of designing a support system for such an unfurling antenna, and "curtain rails","train rails" and "railway catenaries" (examples taken from Visser, 1991). These are analogical leaps between domains whose elements bear no surface similarity. It seems to me that, in order to explain such analogical leaps, more complex structures or mechanisms are required —not instead of, but in addition to recognition.

There have not yet been many serious proposals for such a type of reasoning by analogy. One exception is the interesting analysis put forward by Johnson-Laird (1989) for what he calls "profound analogies".

Johnson-Laird (1989) notices that there are, of course, forms of analogy "that can be retrieved by tractable procedures". The author argues, however, that "the processes underlying the discovery of profound analogies .... cannot be guaranteed by any computationally tractable algorithm" (p. 313). Profound analogies involve "genuine human creativity", which Johnson-Laird (1989) claims, is "nondeterministic".

"The creation of a profound analogy is unlikely to depend on preexisting rules that establish mappings between the source and target domains. The innovation indeed depends on the invention of such rules. ... No algorithm for searching the correct mapping can run in a realistic time beyond a certain number of links." (p. 327) The critical step in finding a profound analog consists in finding the relevant source domain. "The more constraints that individuals can bring to the task —the more they know about potentially relevant domains— the more likely they are to find the illuminating source." (pp. 329-330) Very modestly, Johnson-Laird (1989) concludes that many points made in his paper have been emphasized before by previous theorists. "What, perhaps, has not been noted before are the computational consequences of the exercise of creativity in the discovery of original analogies." (p. 330)

The same arguments used by Simon for the straightforward, elementary nature of ill defined problem solving —i.e. the basically serial character of the problem solving system, and its limited capacity to work on only a few input elements and producing a small number of symbol structures as output[10]— favor, in our opinion, Johnson-Laird's position. The number of links (associations) that are to be traversed

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[10] "There is no way in which a large amount of information can be brought to bear upon these processes locally —that is, over a short period of processing. If a large long-term memory is associated with a serial processor of this kind, then most of the contents of long-term memory will be irrelevant during any brief interval of processing." (Simon, 1973, p. 192)

between source and target structures in remote domains leading to what Johnson-Laird (1989)calls "profound analogies" can, with some plausible degree of probability, be found neither by forward (prospective) search (generation and test), nor by backward (regressive, retrospective) search (means-ends analysis).

This point refers to the "mechanization" premise of the information processing model, questioned by Mayer (1989). Mayer notices that many problems, especially ill defined ones such as design problems, require strategies that are "much less algorithmic and more intuitive than means-ends analysis" (p. 55). It may also illustrate the "concretization" premise. In the information processing approach, each action results in "movement from one concrete state to another. However, ... thinking sometimes occurs at a general or a functional level rather than at the level of specific problem states." (p. 55)

Simon, however, does not consider the need for such "nondeterministic" series of leaps. Design takes place in a context in which "all potentially relevant information" is not fixed, not even present, right from the start[11] —as is required for a problem to be considered well defined. Nevertheless, Simon reasons as if all (design) problems may be solved in one step: either between a process and a subprocess that this process calls via a subroutine structure, or between two symbol structures, the first one evoking the second one via this mechanism that "recognizes when certain information has become relevant" (Simon, 1973, p. 193).

2.2.4. Overestimating the role of problem decomposition

Another example of Simon adopting an approach that cannot account for the problem solving involved in design problems —at least in many industrial design problems— is the role he attributes to decomposition in design.

According to Simon, problem decomposition is a powerful problem-simplification method. Both empirical studies and theoretical analyses, however, show that, even if it may indeed be a strong method, often decomposition brings with it other problems.

Frequently, e.g., several different decompositions of the same design component are possible (Reitman, 1964, p. 296).

Another complication is the following. Simon presents a way in which decomposition can be implemented. It may proceed through the application of "transformational formulas" from the repertoire a profession possesses (Simon, 1973, p. 190). Simon argues that design acquires structure through the application of such "formulas", such as: "house" transforms to "general floor plan plus structure", then "structure" to "support plus roofing plus sheathing plus utilities", etc. Reitman (1964), to whom Simon refers for his "transformational formulas" approach, has imported the idea as an analogy from structural linguistics. Reitman (1964) notes, however, that although it is "a useful analogy, it must not be carried too far": on the basis of innumerable, unforeseeable decisions and information sources, (i) decomposition may follow another order than specified by any transformational formula, and/or (ii) new formulas may be developed.

Furthermore, decomposition is not a simple process that designers may execute in a straightforward manner. Indeed, the multiple interrelations (referred to above as one of design problems characteristics) among the subproblems resulting from a first decomposition, "are likely to be neglected or

[11] Simon even writes that "there is no need for this initial definition" (p. 193).

underemphasized", as Simon himself notes. "Such unwanted side effects accompany all design processes that are as complex as the architectural ones we are considering." (Simon, 1973, p. 191)
Even if, in theory, it is often possible to transform an ill defined problem into a well defined one by closing all open constraints (Reitman, 1964, p. 293), such a transformation corresponds to a form of early commitment that designers generally risk regretting afterwards. Early constraining of variables (constraints) will frequently lead to less than optimal, unsatisfactory design solutions (artifacts). Empirical studies show anyway that designers often avoid early commitment (Guindon, Krasner, & Curtis, 1987).

3. Simon vs. Schön?

In the 1980s, researchers adopting a "situated cognition" perspective, started to propose alternative views on many complex activities. With respect to design, Donald Schön is a representative exponent of this approach.
Schön (1983), adopting a "constructionist" view of design as an activity involving "reflective practice" emphasizes that "problem solving" is generally considered as handling problems which are "given" (as Simon typically does indeed). The process of "problem setting" is neglected. "Problems of choice or decision are solved through the selection, from available means, of the one best suited to established ends. But with this emphasis on problem solving, we ignore problem *setting*, the process by which we define the decision to be made, the ends to be achieved, the means which may be chosen. In real-world practice, problems do not present themselves to the practitioner as givens. They must be constructed from the materials of problematic situations which are puzzling, troubling, and uncertain." (Schön, 1983, pp. 39-40).
Schön (1992, March) considers design as "reflective conversation with the materials of a design situation", a situation that "talks back". He focuses on the situation, which he tries to characterize finely. I am interested in qualifying the characteristics of people —designers— in how they interpret the situation, according to its characteristics —which they identify in the situation. For situated cognition researchers, the situational context is the "dominant resource". I am focusing rather on the way in which people use their resources (especially, their knowledge) in response to the situation. So I am interested in questions such as: which cues are selected in a situation? Depending on which characteristics? And how do they influence the problem-solution development?

N.B. Cognitive ergonomics, especially in France, is inherently situated. It has been thus since its origin and so embedded is this viewpoint that researchers in the domain have never felt the need to use this qualification explicitly. Cognitive ergonomics "is" situated —even if not in the "situated cognition" perspective. One of its main premises is that the characteristics of the situation in which people are working are quintessential for the understanding —and modification— of those people's situations.

The main difference between the "situated cognition" perspective and Simon's seems to us to be one of emphasis. As underlined already above, we agree with authors such as Schön concerning the importance of problem "setting" and "reframing"[12], that is, concerning the "active" and "constructive" aspect of

[12]Other related terms that are found are "redefining" and "reconceptualizing".

problem understanding, which leads to a continuously evolving problem representation. The two approaches are different, but complementary. They focus on different aspects of design.

In his Ph.D. thesis, Dorst (1997) undertakes a comparison of the two approaches, which he qualifies as "the two fundamentally different paradigms that the field [of current design methodology] is based on" (p. 204). He analyzes both, and then conducts an empirical study focusing on what he calls the "integration" activity in design, which is "one of the key issues of design-as-experienced". The two paradigms are evaluated in terms of their ability to describe this integration activity. One of Dorst's main conclusions is that the two paradigms describe distinct parts of the total design activity. They are more or less appropriate for describing the activities in different design phases. Simon's "rational problem solving" paradigm descriptions work best in the "information phase". Seen from this perspective, a designer considers design as a rational problem solving activity, that is "as if it involved objective interpretation". Schön's design perspective is most useful for describing the "conceptual design" phase. Analyzed from this viewpoint, a designer looks at design "as if it involved subjective interpretation". This result leads Dorst to conclude that the choice of the appropriate paradigm depends on three main factors: the goals of the research, the objects of study, and, most importantly, the kind of design activity that is to be studied (pp. 166-167).

4. Conclusion: Some —too late— questions to Simon

I will conclude by three —too late— questions to Simon, which the participants at the conference may perhaps try to answer together.

My first question is: Why does Simon adopt a "subtler" position with respect to economics, than with respect to the psychology of thinking, and especially of design thinking?
With respect to economics, Simon is very sensitive to the way in which economic theories —especially neoclassical ones— idealize human rationality, and neglect its limits. He ascribes this idealization of the human person to these economic theories directing "their attention primarily to the external environment of human thought, to decisions that are optimal for realizing the adaptive system's goals" and "that would be substantively rational in the circumstances defined by the outer environment" (Simon, p. 23). The possibility that the human information processing system may have a limited capability for adaptation is almost totally ignored.
In Simon's view, human economic behavior "illustrates well how outer and inner environment interact and, in particular, how an intelligent system's adjustment to its outer environment ... is limited by its ability, through knowledge and computation, to discover appropriate adaptive behavior." (Simon, 1999, p. 25)
With respect to human behavior in another domain of life, i.e. in situations requiring problem solving, however, Simon seems himself to under-estimate certain limitations, both on human rationality and on human attentional capacities.
In the domain of management science, Simon notices that more or less "rational" methods, i.e. operations research and artificial intelligence, "have been applied mainly to business decisions at the middle level of management. A vast range of top management decisions (e.g., strategic decisions about investment,

R&D, specialization and diversification, recruitment, development, and retention of managerial talent) are still mostly handled traditionally, that is, by experienced executives' exercise of judgment." (Simon, 1999, p. 28) He adds: "As we will see in chapters 3 and 4 [on the psychology of cognition], so-called 'judgment' turns out to be mainly a non-numerical heuristic search that draws upon information stored in large expert memories." (Ibid.)

This under-estimation of design problem solving complexity may be due, in part, to the problems on which the elaboration of the information processing model was based (see above). Simon may consider design —or its prototype or default value, i.e. engineering design— as no more complex than those problems whose solution processes can be covered satisfactorily in terms of search through finite (even if not small) problem spaces. In an introductory section of Ch. 6 "Social planning: designing the evolving artifact", Simon announces that "in the previous chapter representation was discussed mainly in the context of relatively well structured, middle-sized tasks. Representation problems take on new dimensions where social design is involved." (Simon, 1999, p. 141) Here he suggests that differences of at least three types may be involved in the greater "complexity" of social design problems: the more or less well- or ill-definedness of problems, their size, and the nature of their object (engineering or social design problems). In our discussion of the second question, we will come back to this point.

So, it seems that only when he discusses economic and/or social problems that Simon takes into consideration the important role of what he calls "representations without numbers", of evaluation criteria such as "defensibility" of a decision. It is with respect to the problem of regulating automobile emission standards that he writes: "One may regard 'defensibility' as a weak standard for a decision on a matter as consequential as automobile emissions. But it is probably the strictest standard we can generally satisfy with real-world problems of this complexity. [Especially in situations of this kind] an appropriate representation of the problem may be essential to organizing efforts toward solution and to achieving some kind of clarity about how proposed solutions are to be judged. Numbers are not the name of this game but rather representational structures that permit functional reasoning, however qualitative it may be." (Simon, 1999, p. 146)

In the section "Designing without final goals" of this "Social planning" chapter, Simon affirms that processes such as "search guided by only the most general heuristics of 'interestingness' or novelty .... may ... provide the most suitable model of the social design process." (Simon, 1999, p. 162). It was, nevertheless, also this kind of search that he proposed as providing the mechanism for scientific discovery in Ch. 4, "Remembering and learning: memory as environment for thought". Such declarations appearing once in a while in further very straightforward, "simple" or even "simplistic", presentations may well give us food for thought concerning Simon's genuine position.

My second, related, question is: Why does Simon adopt such an inconclusive position with respect to the role of representation in design?

There are indeed several texts in which Simon underlines the importance of representation. He nearly always, however, advances his assertions concerning this importance in a final subsection, and/or presents them as a detail that, even if it is said to be important, "deserves further examination", and is not central to an information processing, problem solving model.

The general reference model for problem solving, presenting its central components was presented in 1972 (Newell & Simon, 1972). "The sciences of the artificial" had already been published in 1969. The

1996, third, edition is presented as a "revised" version in that it contains " new references" that record "the important advances that have been made since 1981 in cognitive psychology ... and the science of design" (p. ix). Indeed, it presents these new references and they are numerous, but they mainly figure in footnotes and the core of the text has not been amended.

On several occasions, Simon starts with a very strict position concerning an issue we consider "critical", nuancing it little by little (e.g. with respect to design consisting in "making a rational choice among a set of given, fixed alternatives", see above). With respect to representations, "finding" them or creating them, he proceeds the other way around. Simon starts by writing: "Every problem solving effort must begin with creating a representation for the problem —a problem space in which the search for the solution can take place." He then continues: "Of course, for most of the problems we encounter in our daily personal or professional lives, we simply retrieve from memory a representation that we have already stored and used on previous occasions." Sometimes, we have to adapt an existing representation. "Occasionally", he admits, a new representation, a new problem space, has to be discovered. "More often", one is midway between simply adapting a known representation and inventing a new representational system.

When he suggests how a new representation comes to life, he proposes that "focus of attention is the key to success —focusing on the particular features of the situation that are relevant to the problem". (Simon, 1999, pp. 108-109) This focus-of-attention idea takes a first step toward building "a theory of representation change" as Simon calls it —I would rather speak of "a theory of representation construction". Simon also speaks of "discovering new representations" as if they have always been there, simply waiting to be discovered. He considers the processes involved in this discovery activity to be "a major missing link in our theories of thinking" and notes that they are "currently a major area of research in cognitive psychology and artificial intelligence (Simon, 1999, p. 109). He refers in this respect to the study by Kaplan and Simon (1990) that indeed proposes some elements for such a theory.

It is the chapter about social planning that leads Simon to expand the "Representation of design problems" topic (Topic 7 of his design curriculum, see above). In this chapter, he also introduces at least six new topics, from "Bounded rationality" to "Designing without final goals" (Simon, 1999, p. 166). Simon notes that "the design tools relevant to these additional topics are in general less formal than those ... described in the previous chapter", i.e. the one on engineering design (Simon, 1999, p. 166).

This observation may inspire our last question: Did Simon think that, depending on the nature of the design object, the cognitive processes and representations involved differ? Would engineering designers proceed in a different way from social planners? Or is it "simply" a question of size? Or a question of the more or less well- or ill-definedness of problems? Does Simon perhaps consider that engineering problems are inherently well defined, and social design problems ill defined? (cf. above)

It is mostly in informal discussions that the question of the influence of the nature of the design object on the design activity has been advanced. With one exception (Ullman, Dietterich, & Staufer, 1988) (as far as we know), no one has set out to answer this question. Ullman, Dietterich and Stauffer (1988) suppose that there is a difference between domains where form and function can be aligned (a functional decomposition corresponds directly to a form decomposition) (e.g., software and circuit design), and domains where individual forms are engineered to do many functions simultaneously (engineering, e.g., mechanical design). An important consequence the authors notice is that in the second type of domain, each design decision can potentially affect every subsequent decision, because a goal may be achieved by modifying a previously specified form, rather than by introducing a new form. The consequence of this characteristic for the cognitive activity is however, not further developed, but a starting point has been provided.

This difference between design domains seems, however, a rather different one than that implicitly introduced by Simon. The idea advanced by Ullman, Dietterich and Stauffer (1988) and the presuppositions I think to identify in Simon's texts, both deserve further examination.

This classic conclusion, calling for "further examination" of questions raised by obtained results, does indeed bring our paper to a close.

* * *

This text has translated our debt —and our gratitude— to Simon. I am thankful, not only because of the basis he has provided for the research on design we, researchers in cognitive psychology and ergonomics, are conducting. Researchers have been taking advantage of this basis for some forty years now. The questions Simon evoked —even provoked—also deserve our gratitude, because they are inspiring, inspiring research and inspiring reading again and again Simon's rich and challenging work.

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